Dynamics of Oceanic Motions

Professor Allan R. Robinson
Division of Engineering and Applied Sciences
Department of Earth and Planetary Sciences
Harvard University
29 Oxford Street
Cambridge, MA 02138-2901
Phone: (617) 495-2819 Fax: (617) 495-5192 Email: robinson@pacific.deas.harvard.edu

Grant #: N000140210989
http://www.deas.harvard.edu/~robinson

LONG-TERM GOALS

This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: the knowledge of realistic regional processes and general physical and physical/acoustical processes; and the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

OBJECTIVES

General objectives are:

(I) To determine for the coastal and/or coupled deep ocean the multiscale processes which occur in:
i) the physical response to external and boundary forcings and via internal dynamical processes;
ii) the physical-biological-chemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
iii) the physical-acoustical interactions which influence acoustic propagation, tomographic inversions, and multi-variate coupled physical-acoustical data assimilation.

(II) To nowcast, forecast and simulate with data assimilation realistic oceanic fields with (sub) mesoscale resolution over large-scale domains and to understand the essential dynamics controlling forecasts and regional predictability. Specific objectives include:
i) studies of Monterey Bay and its interaction with the Californian Current and Undercurrent system;
ii) Northwest Atlantic shelf seas studies with atmospheric and river fluxes;
iii) regional Mediterranean studies;
iv) extension and application of our balance of terms scheme (EVA) to multiscale, interdisciplinary fields with data assimilation;
v) extension and application of our hybrid ESSE data assimilation scheme to interdisciplinary fields and parameter estimation;

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Dynamics of Oceanic Motions**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Division of Engineering and Applied Sciences,,Department of Earth and Planetary Sciences,,Harvard University,29 Oxford Street,,Cambridge,,MA, 02138**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: the knowledge of realistic regional processes and general physical and physical/acoustical processes; and the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

vi) regional predictability studies; and,
vii) theoretical bases for objective adaptive sampling, adaptive modeling and automated verification.

APPROACH

Field estimates are obtained via the melding of data and dynamics in a modular, flexible forecast and simulation system (Harvard Ocean Prediction System - HOPS). Dynamically adjusted fields are used in physical, acoustical and biogeochemical/ecosystem process analyses based on the balance of terms of the dynamical equations. Data assimilation is carried out for dynamical adjustment, dynamical interpolation and data-driven simulations. Assimilation algorithms include a robust "optimal" interpolation scheme and a hybrid method for evolving forecast errors based on an Empirical Orthogonal Function (EOF) representation of the dominant error subspace and an ensemble forecast error estimate (Error Subspace Statistical Estimation - ESSE). The pre-treatment of data before assimilation, via structured data models (e.g. feature models), maximizes the data information content. A sequence of two-way nested model domains and nested observational strategies are used to establish accurate representations of multi-scale processes and interactions.

Energy and Vorticity Analysis (EVA) is a methodology for dynamical process diagnosis. Multi-scale EVA (MS-EVA) is a new version of EVA that is capable of multi-scale energetic studies. We have approached the problem by designing a self-similar, scale-windowed, highly localized transform, called a multi-scale window transform, and then formulating on its basis the multi-scale energetics.

In collaboration with Dr. E Coelho (SACLANTCEN), research has been initiated to extend the HOPS real-time forecasting capability to resolve higher frequencies in space and time (sub-mesoscale and near-inertial tidal motions) and evaluate wind forcing via a Mini-HOPS concept. The Mini-HOPS concept is designed to locally solve the problem of accurate representation of sub-mesoscale synopticity. This concept involves rapid real-time assimilation of high-resolution data in a high-resolution model domain locally nested in a regional model. This approach produces locally more accurate oceanographic field estimates and short-term ocean forecasts and improves the impact of local field high-resolution data assimilation. This is an important conceptual step for data assimilation.

WORK COMPLETED

Two volumes of THE SEA are currently being edited by the principal investigator and K. H. Brink (Vol. 13 – The Global Coastal Ocean: Multiscale Interdisciplinary Processes; Vol. 14 – The Global Coastal Ocean: Interdisciplinary Regional Studies and Syntheses. These are comprehensive interdisciplinary studies that are in the final stage of review and revision. The volumes are scheduled to be published in the last quarter of 2004.

HOPS has been utilized to forecast and investigate the synoptic circulation and transports in the Eastern Ligurian Sea [1] and Tunisia-Sardinia-Sicily [4] regions. The evaluation of the influences of data assimilation, initialization, validation, estimation of parameters, etc. on simulations with coupled physical-biological models has been documented in general [2, 6] and for Massachusetts Bay [3]. Research on the investigation and determination of skill metrics, predictive capabilities and predictability limits was demonstrated in a paper presented at OCEANS02 (Biloxi, MS) in October 2002, "Predictive Skill, Predictive Capability and Predictability in Ocean Forecasting" [5]. The

cooperative research with the ONR program Capturing Uncertainty in the Common Tactical Environmental Picture effort, Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES) was presented at the 16-20 September 2002 Acoustic Variability meeting in La Spezia, Italy [7, 8]. Feature models for the circulation of the Gulf of Maine have been developed and documented [9, 10].

The Multi-Scale Energy and Vorticity Analysis (MS-EVA) methodology has been completed and applied to basic instability processes [15, 16] and a realistic study of the Iceland-Faeroe Front [17]. The MS-EVA approach is currently being applied to determine the dynamical evolution of the upwelling-relaxation phases of the Monterey Bay coastal upwelling with the Aug. 2003 AOSN-II data.

The general analytic theory of advective effects on biological dynamics has analyzed a number of dynamical mechanisms for the production of sub-surface phytoplankton maxima when an upwelling event into the euphotic zone occurs from the nutricline below and a survey of real-ocean biological data to which the theory can be applied and tested has been completed. The Error Subspace Statistical Estimation (ESSE) scheme has been extended to coupled acoustical-physical and biochemical-physical data assimilation. The core of the ESSE software is being distributed to several outside research groups, including MIT scientists as part of the NSF-ITR project "Rapid Real-Time Interdisciplinary Ocean Forecasting: Adaptive Sampling and Adaptive Modeling in a Distributed Environment".

Additional information on the work accomplished for this project is available via the principal investigator's web site: http://www.deas.harvard.edu/~robinson.

RESULTS

The concepts involved in the evaluation and quantitative verification of ocean forecasts and two predictive skill experiments to develop and research these concepts, carried out in the Mediterranean Sea are described in [1 and 5]. Ocean forecasting involves complex ocean observing and prediction systems for ocean regions with multi-scale interdisciplinary dynamical processes and strong, intermittent events. Now that ocean forecasting is becoming more common, it is critically important to interpret and evaluate regional forecasts in order to establish their usefulness to the scientific and applied communities. The Assessment of Skill for Coastal Ocean Transients (ASCOT) project is a series of real-time Coastal Predictive Skill (CPSE) and Rapid Environmental Assessment (REA) experiments and simulations focused on quantitative skill evaluation, carried out by the Harvard Ocean Prediction System group in collaboration with the NATO SACLANT Undersea Research Centre. ASCOT-02 took place in May 2002 in the Corsican Channel near the island of Elba in the Mediterranean Sea. An initial set of objective skill metrics, root-mean-square error and pattern correlation coefficient, have been used to assess the real-time skill of the Harvard Ocean Prediction System. Results from the ASCOT exercises highlight the dual use of data for skill evaluation and assimilation, real-time adaptive sampling and skill optimization and quantitatively demonstrate both real-time and *a posteriori* evaluations of predictive skill and predictive capability. The knowledge and experience gained from ASCOT was applied in 2003 to the June Harvard/SACLANTCEN MREA03/BP03 experiment and the July-September AOSN-II experiment in Monterey Bay and research on the fundamental dynamics of the Monterey Bay circulation system and its coupling to the off-shore California (Under) Current system was carried out as input to the HOPS operational system for this region.

Data assimilation is a modern methodology of relating natural data and dynamical models [3]. The estimation of a quantity of interest via data assimilation involves the combination of observational data with the underlying dynamical principles governing the system under observation. The melding of data and dynamics is a powerful, novel and versatile methodology that makes possible efficient, accurate, and realistic parameter and field estimations otherwise not feasible. All dynamical models are to some extent approximate, and all data sets are finite and to some extent limited by error bounds. The purpose of data assimilation is to provide estimates of nature that are better estimates than can be obtained by using only the observational data or the dynamical model. There are a number of specific approaches to data assimilation that are suitable for estimation of the state of nature, including natural parameters, and for evaluation of the dynamical approximations. Progress is accelerating in understanding the dynamics of real ocean biological–physical interactive processes. Although most biophysical processes in the sea await discovery, new techniques and novel interdisciplinary studies are evolving ocean science to a new level of realism. Generally, understanding proceeds from a quantitative description of four-dimensional structures and events, through the identification of specific dynamics, to the formulation of simple generalizations. The emergence of realistic interdisciplinary four-dimensional data assimilative ocean models and systems is contributing significantly and increasingly to this progress.

Feature-oriented regional modeling for various types of front is presented in a generalized approach in [9]. Large-scale meandering frontal systems such as the Gulf Stream, Kuroshio, etc. can be modeled via velocity-based feature models. Buoyancy forced coastal water mass fronts such as coastal currents, tidal fronts, inflow/outflow fronts, etc. can be modeled by a generalized parameterized water mass feature model. The multi-scale synoptic circulation systems in the Gulf of Maine and Georges Bank region are summarized using a feature-oriented approach in [10]. A synoptic initialization scheme for feature-oriented regional modeling and simulation of the buoyancy-driven circulation in the coastal-to-deep region has been developed. The applicability of feature-oriented regional modeling and simulation for multi-scale, multi-domain, multi-platform and multi-disciplinary nested forecast systems has been demonstrated.

Multi-Scale Energy and Vorticity Analysis (MS-EVA) is a new methodology for the investigation of fundamental processes from real oceanic and atmospheric data for complex dynamics which are nonlinear, time and space intermittent, and involving multi-scale interactions [15, 16]. Based on a functional analysis tool, Multiscale Window Transform (MWT), this methodology allows the study of GFD processes locally by investigating the complicated transport, perfect transfer, buoyancy conversion, and dissipation/diffusion processes, and determining the intricate relationship between different scale windows. The MS-EVA is expected to provide a path to sub-grid process parameterization and facilitate adaptive sampling in real-time operations.

A localized stability analysis for real-time objective identification of baroclinic and barotropic instabilities from ocean forecasts has also been developed. It is local in space and time and independent of any boundaries, a conceptual generalization of the classical formalism. With the aid of MWT and MS-EVA, the identification is reduced to a set of simple criteria and can be easily to be incorporated into forecast models. As a real ocean application, the MS-EVA has been used to diagnose the dynamics of the Iceland-Faeroe Front (IFF) [17]. An MS-EVA-ready dataset was first generated from a hindcast with the Harvard Ocean Prediction System (HOPS), using the hydrographic data obtained during a 1993 survey in that region. The calculated energetics, when locally averaged, reveal that the formation of the observed mesoscale meander is a result of both a baroclinic instability and a

barotropic instability, with the former dominant in the western region at mid-depths, while the latter is more active in surface layers.

IMPACT/APPLICATIONS

The important ESSE concept is that the evolution of 3D multivariate forecast variability and error can be efficiently described by a small number of adequate functions (e.g. error EOFs). The most energetic variability and error fields are expected to evolve in limited subspaces. In general, ESSE is useful for a wide range of applications, including nonlinear field and error forecasting, finding numerical instabilities, performing predictability studies, objective analyses, data-driven simulations, adaptive sampling and parameter estimation.
Analytic theory and numerical simulations have improved our understanding of the biological response to physical processes in fronts and mesoscale patches. The role of coupled biological/physical data assimilation and application of existing methods is an important focus of our research. Since data assimilation intimately links dynamical models and observations, it can play a critical role in the important area of fundamental biological oceanographic dynamical model development and validation over a hierarchy of complexities. The emergence of realistic interdisciplinary four-dimensional data assimilative ocean models and systems is contributing significantly and increasingly to this progress. A major step has been the realization of the multi-variate coupled physical-acoustical data assimilation.

Real-time regional forecasting research results are directly applicable to the design of ocean prediction and monitoring systems for: naval operations; research operations; the efficient environmental management of, and commercial operations within, a multi-use Exclusive Economic Zone; and, interdisciplinary global change research.

TRANSITIONS

Definitive results are passed to the Harvard 6.2 research “Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)" with the same principal investigator and from there transitioned to other research groups. The integration of HOPS into the AOSN system has been initiated with the August 2003 experiment. The ESSE methodologies and codes continue to be transferred to ROMS-TOMS in collaboration with Rutgers University.

RELATED PROJECTS

This project is closely related to other Harvard projects, including: an NSF-OIT project "Rapid Real Time Interdisciplinary Ocean Forecasting Adaptive Sampling and Adaptive Modeling in a Distributed Environment" (Prof. N. Patrikalakis and Prof. H. Schmidt - MIT; Prof. J.J. McCarthy - Harvard); the ONR project "Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture", and other Harvard research. In addition, important collaborations are ongoing with University of Massachusetts-Dartmouth (Prof. A. Gangopadhyay), NRL Stennis (Dr. A. Warn-Varnas); IMGA, Modena, Italy (Dr. N. Pinardi); and the Naval Postgraduate School (Dr. Ching-Sang Chiu).

PUBLICATIONS

[1] Robinson, A.R., J. Sellschopp, W.G. Leslie, R. Onken, A. Alvarez, G. Baldasserini, P.J. Haley, Jr., P.F.J. Lermusiaux, C. Lozano, E. Nacini, R. Stoner and P. Zanasca (2003) Real-Time Forecasting of Synoptic Transients in the Eastern Ligurian Sea. Bovio, E., R. Tyce and H. Schmidt (Editors), Autonomous underwater vehicle and ocean modeling networks: GOATS 2000. Proceedings of a conference held in La Spezia, Italy, NATO SACLANT Undersea Research Centre, *SACLANTCEN Conference Proceedings Series* CP-46.

[2] Gregoire, M., P. Brasseur and P.F.J. Lermusiaux (Guest Editors) (2003) The use of data assimilation in coupled hydrodynamic, ecological and bio-geo-chemical models of the ocean. Special Issue, 33rd International Liege colloquium, May 2001. *J. of Marine Systems*, **40**, 1-3.

[3] Besiktepe, S.T., P.F.J. Lermusiaux and A.R. Robinson (2003) Coupled physical and biological data driven simulations of Massachusetts Bay in late summer: Real-time and post-cruise data assimilation. Special Issue on "The use of data assimilation in coupled hydrodynamic, ecological and bio-geo-chemical models of the oceans," Gregoire M., P. Brasseur and P.F.J. Lermusiaux (Editors), *Journal of Marine Systems*, **40**, 171-212.

[4] Onken, R., A.R. Robinson, P.F.J. Lermusiaux, P.J. Haley, Jr., and L.A. Anderson (2003) Data-driven Simulations of Synoptic Circulation and Transports in the Tunisian-Sardinia-Sicily Region. *Journal of Geophysical Research*, **108** (C9), 8123-8135.

[5] Robinson, A.R., P.F.J. Lermusiaux, P.J. Haley, Jr. and W.G. Leslie (2002) Predictive Skill, Predictive Capability and Predictability in Ocean Forecasting. *Proceedings of* O*ceans 2002 IEEE/MITS Conference*, 787-794.

[6] Lermusiaux, P.F.J., A.R. Robinson, P.J. Haley, Jr. and W.G. Leslie (2002) Advanced Interdisciplinary Data Assimilation: Filtering and Smoothing via Error Subspace Statistical Estimation. *Proceedings of Oceans 2002 IEEE/MITS Conference*, 795-802.

[7] Robinson, A.R., P. Abbot, P.F.J. Lermusiaux and L. Dillman (2002) Transfer of uncertainties through physical-acoustical-sonar end-to-end systems: A conceptual basis. *Acoustic Variability 2002*. N.G. Pace and F.B. Jensen (Editors), SACLANTCEN. Kluwer Academic Press, 603-610.

[8] Lermusiaux, P.F.J. and C.-S. Chiu (2002) Four-dimensional data assimilation for coupled physical-acoustical fields. *Accoustic Variability, 2002*. N.G. Pace and F.B. Jenson (Editors), SACLANTCEN. Kluwer Academic Press 417-424.

[9] Gangopadhyay, A., A.R. Robinson, P.J. Haley, Jr., W.G. Leslie, C.J. Lozano, J.J. Bisagni and Z. Yu (2003) Feature Oriented Regional Modeling and Simulations (FORMS) in the Gulf of Maine and Georges Bank. *Continental Shelf Research*, **23** (3-4), 317-353.

[10] Gangopadhyay, A. and A.R. Robinson (2002) Feature-Oriented Regional Modeling of Oceanic Fronts. *Dynamics of Atmospheres and Oceans*, **36**, 201-232.

PUBLICATIONS (IN PRESS AND SUBMITTED)

[11] Robinson, A.R. and W.G. Leslie (2003) Advanced Systems for Operational Ocean Forecasting of Interdisciplinary Fields and Uncertainties. Proceedings of the MREP2003 Conference (R. Tyce, editor), SACLANTCEN. [In Press]

[12] Robinson, A.R. and P.F.J. Lermusiaux (2003) Prediction Systems with Data Assimilation for Coupled Ocean Science and Ocean Acoustics. Proceedings of the Sixth International Conference on Theoretical and Computational Acoustics (A. Tolstoy, et al., editors), World Scientific Publishing. [In Press]

[13] Sundermeyer, M.A., B.J. Rothschild and A.R. Robinson (2003) Environmental indicators and the predictability of commercial fish stocks, Part II: Evaluation using spacially explicit models. *Fisheries Oceanography*. [In Press]

[14] Sundermeyer, M.A., B.J. Rothschild and A.R. Robinson (2003) Environmental indicators and the predictability of commercial fish stocks, Part I: An empirical approach using commercial landing data. *Fisheries Oceanography*. [In Press]

[15] Liang, X.S., and A.R. Robinson (2003) Localized Multiscale Energy and Vorticity Analysis: I. Fundamentals. *Dynamics of Atmospheres and Oceans.* [Submitted]

[16] Liang, X.S., and A.R. Robinson (2003) Localized Multiscale Energy and Vorticity Analysis: II. Instability theory and validation. *Dynamics of Atmospheres and Oceans.* [Submitted]

[17] Liang, X.S., and A.R. Robinson (2003) A study of the Iceland-Faeroe Frontal variability with the Multiscale Energy and Vorticity Analysis. *Journal of Physical Oceanography.* [Submitted]